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SPECTRAL CHARACTERISTICS OF THE MARINE SURFACE LAYER

FINAL REPORT
GRANT NUMBERS: N00014-93-1-0271 & N00014-96-1-0012

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11 April 2000

I. Introduction

The goal of this research is to gain a better understanding of the flow characteristics of the marine surface layers, including the coupling at the air-sea interface. Specifically, the research focuses on the influence of ocean waves on turbulent processes, especially those involved in stress-wave interactions. The long range goal of this research is to develop new and/or revise old theoretical descriptions of turbulence, such that they are universally applicable to both over land and over sea boundary layers. This is to be accomplished by focusing on the physical processes unique to the marine boundary layers through a combination of scale analysis and numerical modeling.

II. Scientific Objectives

The PI's first objective is to improve our understanding of flux profile relationships over the ocean using our profile measurements in the kinetic energy, momentum, and scalar variance budget equations. This involves an investigation of the applicability of Monin-Obukhov (MO) similarity theory to over-ocean measurement in order to determine these functions and their proportionality factors (e.g., the von Karman and Kolmogorov constants). That is, the goal is to determine these functions over the open ocean where a difference with land derived functions is possible due to the fluid ocean surface. The PI's second objective in this research is to investigate how the wave induced flow affects the turbulent processes in the marine surface layer. In these studies the PI focused on the role that stress/wave interaction plays in modifying the magnitude and direction of the momentum and energy flux within the wave boundary layer (WBL).

III. Approach

The Marine Boundary Layers (MBL) Accelerated Research Initiative centers around two field programs designed to examine the 3-D structure of the marine boundary layers: the Risø Air-Sea Experiments (RASEX) conducted in shallow water off the coast of Denmark, and the MBL Main Experiments conducted in deep water off the California coast. In these experiments we deployed fast response and mean sensors to investigate the vertical structure of the atmospheric surface layer (lowest 10% of the marine boundary layer). The overall structure of the atmospheric boundary layer is being investigated by coupling these measurements with remotely sensed variables (e.g., lidar, wind profiler, and sodar) and rawinsonde launches. Horizontal variability is being investigated by combining all of the above with data taken from research vessels, microwave radars, and a research aircraft. The oceanic boundary layer is being investigated with a similar set of instrumentation, including sonars, drifting buoys, current meters, towed instruments and vertical profilers. These two boundary layers are then coupled together using simultaneous measurements of the wave field. This involved the deployment of wave-wire arrays and remote sensing instrumentation on both sides of the interface.

Our approach has involved the usual Reynold's decomposition of the measured signals into mean and turbulent components to investigate whether the fluxes obey MO similarity. Additionally, we are using more innovative techniques to further decompose the fluctuating signal into turbulent and wave-induced components. The latter involves the use of traditional phase averaging, more sophisticated approaches involving Hilbert transforms, and a new similarity theory involving wave-pressure and wave-velocity correlations. The separation of the flow into wave-induced and turbulent components simplifies the interpretation of the data by allowing us to study the processes separately.

IV. Results

Our investigation of MO similarity demonstrated that the theory is valid in the marine surface layer as long as it is applied to turbulence statistics taken above the wave boundary layer (*Edson and Fairall,* 1998b). This study found that the TKE budget is well described by a balance between production and dissipation except for slightly unstable conditions where production exceeds dissipation by as much as 17%. We have argued that this is due to a local imbalance between the pressure and energy transport. Over developing surface waves, part of the energy flux entering the surface layer is not dissipated into thermal energy, but rather is transported to the surface to generate and sustain waves and currents. This energy flux is expected to result in a "dissipation deficit" in the volume-averaged dissipation rate that would result in local production exceeding dissipation. We would expect the dissipation deficit to be greatest over the youngest seas where the energy flux is largest. Evidence for this effect is given by *Edson et al.* (1997b), which showed that the younger the seas the greater the deficit.

The challenge is to derive parameterizations that account for the flux of kinetic energy into the ocean as a function of sea state. We are currently working on the hypothesis that observed dissipation deficit is due to a pressure transport term that is sea-state dependent. This proposition seems reasonable since the pressure flux evaluated at the surface, $\overline{wp}_o$, represents the energy flux into the waves. In our initial investigations, the RASEX data is being used to directly study the role of the pressure transport term in the turbulent kinetic energy equation (*Wilczak et al.*, 1999). The combination of the surface slope and pressure sensor measurements have allowed us to directly measure the component of the momentum flux associated with form drag. The doctoral research conducted at WHOI by Dr. Jeffrey Hare resulted in a new similarity theory involving wave-pressure and wave-velocity correlations (*Hare et al.*, 1997). This work has provided a better understanding of the complex vertical structure of momentum and energy exchange in the WBL.

The FLIP measurements are now being used to study the influence of waves on the transport of energy (*Edson et al.*, 1997b) and momentum (*Miller et al.*, 1998) to and from the ocean surface. In particular, we are investigating the influence of the dominant, wind-driven, surface waves on the vertical flux of horizontal momentum in the marine surface layer over open ocean conditions. Investigations with our students of the vertical structure of the WBL have led to new techniques to describe the behavior of near surface turbulence by decomposing the measured signals into mean, wave-induced, and turbulent components using traditional phase averaging (*Wetzel et al.*, 2000), and more sophisticated approaches involving Hilbert transforms (*Hristov et al.*, 1998). Once the signal has been decomposed, the wave-induced component of the horizontal and vertical can be combined to provide vertical profiles of the wave-induced momentum flux. These results are now being used to investigate both the magnitude and sign of this flux as a function of sea state. For example, the study conducted by *Wetzel et al.* (2000) showed a wave-induced momentum flux to the waves in developing seas and a flux from waves to wind over decaying seas.

These and other investigations are described in detail in the following papers, which acknowledge support from these grants. The papers that list the PI as first author are included along with the article submitted by Suzanne Wetzel, which describes the thesis work she conducted with the PI.

A. Refereed Publications

1996 Mahrt, L., D. Vickers, J. Howell, J. Højstrup, J.M. Wilczak, J.B. Edson, and J.E. Hare, "Sea surface drag coefficients in RASEX," *J. Geophys. Res., 101*, 14327-14335.

1997 Hare, J.E., T. Hara, J.B. Edson, and J.M. Wilczak, "A similarity analysis of the structure of air flow over surface waves," *J. Phys. Oceanogr., 27*, 1018-1037.

1998a Edson, J.B., A. A. Hinton, K. E. Prada, J.E. Hare, and C.W. Fairall, "Direct covariance flux estimates from mobile platforms at sea," *J. Atmos. Oceanic Tech., 15*, 547-562

1998b Edson, J.B., and C.W. Fairall, "Similarity relationships in the marine atmospheric surface layer for terms in the TKE and scalar variance budgets," *J. Atmos. Sci., 55*, 2311-2328.

1998 Mahrt, L., D. Vickers, J. Edson, J. Sun, J. Højstrup, J. Hare, and J.M. Wilczak, "Heat flux in the coastal zone", *Bound.-Layer Meteorol., 86*, 421-446.

2000 Mahrt, L., D. Vickers, J. Edson, J.M. Wilczak, and J. Hare, "Boundary-layer transitions in offshore flow", *Bound.-Layer Meteorol.*, accepted.

2000 Wetzel, S.W., J.B. Edson, T.S. Hristov, S.D. Miller, and C.A. Friehe, "Wave-induced momentum flux over open ocean waves," *J. Phys. Oceanogr.*, in revision.

B. Conference Extended Abstracts

1995 Hare, J., J. Edson, J. Wilczak, T. Hara, L. Mahrt, and J. Højstrup, "An investigation of stress-wave interaction during the RASEX program," *The 11th Symposium on Turbulence and Diffusion*, Charlotte, NC.

1995 Mahrt, L., D. Vickers, J. Howell, J. Højstrup, J. Edson, and J. Hare, "Dependence of the drag coefficient on averaging scale and flux sampling problems, application to RASEX," *The 11th Symposium on Turbulence and Diffusion*, Charlotte, NC, 485-488.

1995 Wilczak, J., A. Bedard, J. Edson, J. Hare, J. Højstrup, and L. Mahrt "Pressure transport measured on a sea mast during the RASEX program," *The 11th Symposium on Turbulence and Diffusion*, Charlotte, NC.

1997a Edson, J., and C. Fairall, "Examination of the Kansas relationships for TKE and scalar budgets over the ocean," *Proc. 12th Symp. on Boundary Layers and Turbulence*, Vancouver, BC, AMS, Boston, MA, 589-590.

1997b Edson, J., S. Wetzel, C. Friehe, S. Miller, and T. Hristov, "Energy flux and dissipation profiles in the marine surface layer," *Proc. 12th Symp. on Boundary Layers and Turbulence*, Vancouver, BC, AMS, Boston, MA, 314-315.

1997 Hare, J. E., J. M. Wilczak, C. W. Fairall, T. Hara, and J. B. Edson, "The statistical structure of air flow over sea swell," *Proc. 12th Symp. on Boundary Layers and Turbulence*, Vancouver, BC, AMS, Boston, MA, 285-286.

1997 Hristov, T., C. Friehe, S. Miller, J. Edson, and S. Wetzel, "Structure of the atmospheric surface layer over the ocean waves - phase averaging via the Hilbert transform," *Proc. 12th Symp. on Boundary Layers and Turbulence*, Vancouver, BC, AMS, Boston, MA, 283-284.

1997 Miller, S., C. Friehe, T. Hristov, and J. Edson, "Wind and turbulence profiles in the surface over the ocean," *Proc. 12th Symp. on Boundary Layers and Turbulence*, Vancouver, BC, AMS, Boston, MA, 308-309.

1997 Rogers, A., H. N. Shirer, G. S. Young, L. Suciu, R. Wells, J. B. Edson, S. W. Wetzel, C. Friehe, T. Hristov, and S. Miller, "Using the chaotic behavior of the time series observed on FLIP to identify MABL coherent structures," *Proc. 12th Symp. on Boundary Layers and Turbulence*, Vancouver, BC, AMS, Boston, MA, 243-244.

1997 Wilczak, J., J. Edson, T. Hara, J. Hojstrup, and J. Hare, "The turbulent kinetic energy budget during RASEX," *Proc. 12th Symp. on Boundary Layers and Turbulence*, Vancouver, BC, AMS, Boston, MA, 312-313.

1998 Hristov, T., S. Miller, C. Friehe, J. Edson, and S. Wetzel, "Structure of the atmospheric surface layer over open ocean waves: Representation in terms of phase averages," *Proc. Conf. Wind-Over-Wave Couplings: Perspectives and Prospects*, Salford University, UK.

1998 Miller, S., J. Edson, T. Hristov, C. Friehe, and S. Wetzel, "Wind and turbulence profiles in the surface layer over ocean waves," *Proc. Conf. Wind-Over-Wave Couplings: Perspectives and Prospects*, Salford University, UK.

1999 Hristov, T., C. Friehe, S. Miller, and J. Edson, "Indentification and analysis of wind-wave interactions in field experiment data," *Proc. 13th Symp. on Boundary Layers and Turbulence*, Dallas, TX, AMS, Boston, MA, 233-236.

1999 Miller, S., C. Friehe, T. Hristov, and J. Edson, "The wave-induced wind field above deep water waves," *Proc. 13th Symp. on Boundary Layers and Turbulence*, Dallas, TX, AMS, Boston, MA, 237-240.

C. Book Chapters

1999 Hara, T., J. E. Hare, J. B. Edson, and J. M. Wilczak, "Effect of surface gravity waves on near-surface atmospheric turbulence," in *Air-Sea Exchange: Physics, Chemistry and*

Dynamics, G. L. Geernhaert, ed., Kluwer Academic Pub., Boston, pp. 127-152.

1999 Shirer, H., G. Young, R. Wells, A. Rogers, J. Rishel, R. Mason, L. Suciu, N. Winstead, H. Henderson, D. Rinker, J. Rohrbach, J. Edson, C. Friehe, S. Wetzel, S. Miller, and T. Hristov, "Identifying coherent structures in the marine atmosphere," in *Air-Sea Exchange: Physics, Chemistry and Dynamics*, G. L. Geernhaert, ed., Kluwer Academic Pub., Boston, pp. 463-506.

1999 Wilczak, J. M., J. B. Edson, J. Høstrup, and T. Hara, "The budget of turbulent kinetic energy in the marine atmospheric surface layer," in *Air-Sea Exchange: Physics, Chemistry and Dynamics*, G. L. Geernhaert, ed., Kluwer Academic Pub., Boston, pp. 153-174.

2000 Hristov, T., S. Miller, C. Friehe, J. Edson, and S. Wetzel, "Structure of the atmospheric surface layer over open ocean waves: Representation in terms of phase averages," in *Wind-Over-Wave Couplings: Perspectives and Prospects*, Institute of Mathematics and Its Applications, Salford University, UK, in press.

2000 Miller, S., J. Edson, T. Hristov, C. Friehe, and S. Wetzel, "Wind and turbulence profiles in the surface layer over ocean waves," in *Wind-Over-Wave Couplings: Perspectives and Prospects*, Institute of Mathematics and Its Applications, Salford University, UK, in press.

V. Impact

These results have had a profound impact on the modeling community. As a result, we have been asked to give briefings and seminars on these results at the Naval Research Laboratory in Monterey and at the National Center for Atmospheric Research in Boulder. The results are also impacting the way that researcher interpret the measurements taken from ocean observing system. For example, it has been long known that flux estimates from indirect methods require additional parameterizations to account for wave-induced effects. Our MBL investigations are now providing a clearer picture of the physical processes in the wave boundary layer responsible for effects.

VI. Related Projects

The work involved in the MBL ARI nicely complements the research objectives of our involvement in the NSF's Coastal Ocean Processes Study. Our component of this program is aimed at investigating the role of surface waves and atmospheric forcing in air-sea gas exchange. Sean McKenna, a WHOI/MIT Joint Program student, is using an AASERT to investigate the role of surfactants in air-sea interaction. Preliminary results from this effort were given at the AMS meeting in Dallas (Edson et al., 1999). The MBL program is also providing important information to the Coastal Mixing and Optics (CMO) ARI. The FLIP measurements have greatly assisted the PI in interpreting the data he collects from a sonic anemometer mounted on the central mooring of the CMO array. In particular, the FLIP analysis has allowed the PI to adjust his inertial-dissipation estimates of the momentum flux to take into account some of the influences of the wave-induced flow. The results from the two programs have been combined in a Master's thesis by Michiko Martin (1998), a naval student in the WHOI/MIT Joint Program.

1998 Martin, M. J., *An Investigation of Momentum Exchange Parameterizations and Atmospheric Forcing for the Coastal Mixing and Optics Program*, Master's Thesis, WHOI/MIT Joint Program, 83 pp.

1999 Edson, J. B., S. P. McKenna, W. R. McGillis, and N. M. Frew, "Atmospheric forcing and energy exchange during the 1997 CoOP gas exchange experiment," *Proc. 13th Symp. on Boundary Layers and Turbulence*, Dallas, TX, AMS, Boston, MA, 351-354.

Similarity Relationships in the Marine Atmospheric Surface Layer for Terms in the TKE and Scalar Variance Budgets*

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(Manuscript received 3 September 1996, in final form 25 October 1997)

ABSTRACT

Measurements of the momentum, heat, moisture, energy, and scalar variance fluxes are combined with dissipation estimates to investigate the behavior of marine surface layer turbulence. These measurements span a wide range of atmospheric stability conditions and provide estimates of z/L between -8 and 1. Second- and third-order velocity differences are first used to provide an estimate of the Kolmogorov constant equal to 0.53 $\pm$ 0.04. The fluxes and dissipation estimates are then used to provide Monin–Obukhov (MO) similarity relationships of the various terms in the turbulent kinetic energy (TKE) and scalar variance (SV) budgets. These relationships are formulated to have the correct limiting forms in extremely stable and convective conditions. The analyses concludes with a determination of updated dimensionless structure function parameters for use with the inertial–dissipation flux method.

The production of TKE is found to balance its dissipation in convective conditions and to exceed dissipation by up to 17% in near-neutral conditions. This imbalance is investigated using the authors' measurements of the energy flux and results in parameterizations for the energy flux and energy transport term in the TKE budget. The form of the dimensionless energy transport and dimensionless dissipation functions are very similar to previous parameterizations. From these measurements, it is concluded that the magnitude of energy transport (a loss of energy) is larger than the pressure transport (a gain of energy) in slightly unstable conditions.

The dissipation of SV is found to closely balance production in near-neutral conditions. However, the SV budget can only be balanced in convective conditions by inclusion of the transport term. The SV transport term is derived using our estimates of the flux of SV and the derivative approach. The behavior of the derived function represents a slight loss of SV in near-neutral conditions and a gain in very unstable conditions. This finding is consistent with previous investigations.

The similarity between these functions and recent overland results further suggests that experiments are generally above the region where wave-induced fluctuations influence the flow. The authors conclude that MO similarity theory is valid in the marine surface layer as long as it is applied to turbulence statistics taken above the wave boundary layer.

1. Introduction

Our understanding of the behavior of turbulence in the atmospheric surface layer was vastly improved by a number of overland field experiments conducted during the late 1960s and 1970s. These include the landmark 1968 Kansas (Izumi 1971) experiment, the 1973 Minnesota (Champagne et al. 1977) experiment, and the 1976 International Turbulence Comparison Experiment (Dyer and Bradley 1982). These experiments led to the validation of a powerful set of statistical tools derived from Monin–Obukhov similarity theory. The semiempirical relationships derived from their carefully conducted measurements are now used extensively in the lower boundary conditions of numerical forecast models where one must derive turbulent quantities from the mean variables available from the model. Similarly, these relationships are often used to estimate the desired turbulent quantities from mean measurements over the ocean where direct measurement of the fluxes is very difficult. However, the use of overland measurements to infer surface fluxes over the open ocean raises questions about the universality of these relationships.

There have been a number of experiments to investigate the structure of atmospheric turbulence in the marine boundary layer (Smith et al. 1996). These include the 1969 Barbados Oceanographic and Meteorological

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Direct Covariance Flux Estimates from Mobile Platforms at Sea*

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(Manuscript received 14 December 1995, in final form 22 April 1997)

ABSTRACT

This paper describes two methods for computing direct covariance fluxes from anemometers mounted on moving platforms at sea. These methods involve the use of either a strapped-down or gyro-stabilized system that are used to compute terms that correct for the 1) instantaneous tilt of the anemometer due to the pitch, roll, and heading variations of the platform; 2) angular velocities at the anemometer due to rotation of the platform about its local coordinate system axes; and 3) translational velocities of the platform with respect to a fixed frame of reference. The paper provides a comparison of fluxes computed with three strapped-down systems from two recent field experiments. These comparisons shows that the direct covariance fluxes are in good agreement with fluxes derived using the bulk aerodynamic method. Additional comparisons between the ship system and the research platform *FLIP* indicate that flow distortion systematically increases the momentum flux by 15%. Evidence suggests that this correction is appropriate for a commonly used class of research vessels. The application of corrections for both motion contamination and flow distortion results in direct covariance flux estimates with an uncertainty of approximately 10%–20%.

1. Introduction

In recent years a great deal of attention has been directed toward air–sea interaction as scientists have begun to study environmental issues by properly treating the ocean and atmosphere as a coupled system. This approach has resulted in a number of air–sea interaction studies, which have united scientists from a variety of disciplines. These studies have also forced researchers to address the problems associated with making high-resolution measurements of turbulence statistics at sea. The problems largely arise from three sources: platform motion, flow distortion, and environmental factors unique to the ocean.

Some of the environmental factors that prove troublesome include the contamination of temperature probes by sea spray (Friehe et al. 1975; Larsen et al. 1993) and mechanical failure induced by a combination of corrosion, wave stress, and unavoidable neglect due to infrequent maintenance. Many of these problems have been overcome by the use of the latest generation of sonic anemometers–thermometers. However, sea-spray contamination of fast-response humidity sensors still plagues marine meteorologists. Dual-wavelength infrared hygrometers have shown some promise in combating this problem in recent field experiments. Unfortunately, these devices often present additional problems (e.g., Fairall and Young 1991), which make the development of a reliable fast-response humidity sensors one of the greatest challenges in marine instrumentation.

Attempts have been made to combat the problems of platform motion and flow distortion by choosing indirect measurement techniques that are less sensitive to their contaminating effects. An example of an indirect measurement is the use of the inertial-dissipation method to infer meteorological fluxes from spectral estimates in the inertial subrange (Fairall and Larsen 1986; Fairall et al. 1990). This method is commonly used on research vessels because the inertial subrange estimates are generally uncontaminated by wave-induced motion. The method has also been shown by Edson et al. (1991) to be less sensitive to flow distortion because it is based

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K.4 EXAMINATION OF THE KANSAS RELATIONSHIPS FOR TKE AND SCALAR BUDGETS OVER THE OCEAN

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1. INTRODUCTION

Our understanding of the behavior of turbulence in the atmospheric surface layer was vastly improved by a number of overland field experiments conducted during the late sixties and seventies. The most noteworthy of these was the landmark 1968 Kansas experiment (Wyngaard and Coté, 1971). These experiments led to the validation of a powerful set of statistical tools derived from Monin-Obukhov (MO) similarity theory.

The semi-empirical relationships derived from these experiments are now used extensively in the lower boundary conditions of numerical forecast models where one must derive turbulent quantities using the mean variables available from the model. Similarly, these relationships are often used to estimate the desired turbulent quantities from mean measurements over the ocean where direct measurement of the fluxes is very difficult. However, the use of overland measurements to infer surface fluxes over the ocean raises questions about the universality of these relationships.

In this abstract we present some data taken in the marine surface layer during two separate field experiments. Our goal is to verify and extend the overland results for application over the oceans, including a close look at the relative balance of dissipation and production in the TKE and scalar variance (hereafter, SV) budgets. These new measurements feature eddy correlation stress and heat flux estimates over a wide range of stabilities. The TKE and SV dissipation rates are computed from the inertial subrange of the spectra measured using sonic anemometer/thermometers and infrared hygrometers.

2. MO SIMILARITY

The structure of the turbulent flow in the constant flux (surface) layer over land is influenced by both mechanical and thermal forcing. Monin and Obukhov (1946, 1954) were the first to describe a similarity hypothesis about the statistical nature of the turbulent flow based on the relative strength of these two forcing mechanisms. MO similarity theory states that the structure of turbulence is determined by the height above the surface, z, the buoyancy parameter, g/Θ_v, the friction velocity, u_*, and the buoyancy flux, $\overline{w\theta_v}$.

These governing parameters can be combined to form an additional velocity scale; two temperature and humidity scales defined as

$$u_f = \left(\frac{zg}{\Theta_v}\overline{w\theta_v}\right)^{1/3}, \quad x_* = -\frac{\overline{wx}}{u_*}, \quad x_f = -\frac{\overline{wx}}{u_f} \tag{1}$$

where $x = \theta, q$; and a length scale, L, now known as the Monin Obukhov length

$$L = -\frac{\Theta_v}{g\kappa}\frac{u_*^3}{\overline{w\theta_v}}, \tag{2}$$

where κ is the von Karman constant. The magnitude of the M-O length is determined by the relative strength of the mechanical versus thermal forcing.

The various scales are not independent (Wyngaard 1973) as they can be combined to obtain relationships such as $u_f/u_* = (-z/L)^{1/3}$. Therefore, it is common practice to select u_*, T_*, and q_* as the scaling parameters. However, in very light winds conditions, MO similarity requires that the surface stress (i.e., u_*) is no longer a relevant scaling parameter. The structure of the surface layer under these conditions approaches that of local free convection (Tennekes 1970), where it is more appropriate to use the convective scaling parameters denoted by the subscript f. The similarity hypothesis then states that various turbulent statistics when normalized by these scaling parameters are universal function of z/L. This hypothesis has been validated by a number of studies in the atmospheric boundary layer over land including the Kansas, Minnesota and ITCE experiments.

In addition to the constant flux layer constraint, the application of MO similarity theory to the marine surface layer requires some caution because the scaling parameters are only meant to account for the influence of mechanical and thermal forcing on the turbulence. Many investigations have demonstrated that additional scaling parameters are required to describe turbulent variables within the wave boundary layer (WBL), where the total momentum flux, even if assumed to be constant with height, has an appreciable wave induced component.

Our measurements indicate that we are generally well above the WBL for measurements under very stable and unstable conditions. However, we believe that we are experiencing some wave-induced effects at near neutral conditions even at our measurement heights above 10 m. These effects are most evident in our TKE dissipation measurements, while the terms in the SV budgets appear to be unaffected by the wave-induced flow at this height.

3. SCALAR VARIANCE BUDGETS

In homogeneous and steady-state conditions, the dimensionless SV budgets are given by

$$\phi_{N_x}(\zeta) = \frac{N_x \kappa z}{u_* x_*^2} = \phi_x(\zeta) - \phi_{tx}(\zeta) \tag{3}$$

where $\zeta = z/L$ and N_x is one-half the dissipation rate of either temperature or humidity variance. The three terms ϕ_{N_x}, ϕ_x, and ϕ_{tx} represent the dissipation, production, and transport of SV,

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13.7 ENERGY FLUX AND DISSIPATION PROFILES IN THE MARINE SURFACE LAYER

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1. INTRODUCTION

Investigations of atmospheric turbulence over the world's oceans have shown that the interaction of wind with surface waves results in flow characteristics that differ substantially from even a horizontally homogeneous surface layer over land. As a result, marine meteorologists and physical oceanographers often divide the boundary layer close to the surface into the surface layer where Monin-Obukhov (MO) similarity holds, and a wave boundary layer (WBL) where additional scaling parameters are required for similarity. Even though the search for these scaling parameters and hypotheses for their use has been going on for many years (e.g., Miles, 1957; Hare et. al, 1997), we are still a long way from a consensus in the scientific community.

In this paper we present some of our on-going investigations of turbulence and wave-induced flow in the marine surface layer. These investigations rely on a set of data collected from the R/P FLIP during the Marine Boundary Layers (MBL) experiment sponsored by the Office of Naval Research. Specifically, this paper examines the energy flux and its relationship to its rate of dissipation within the marine boundary layer. The flux of kinetic energy, $F(z)$, into a layer of air over a horizontally homogeneous surface is given by

$$F(z) = \overline{u'w'}U(z) + \overline{v'w'}V(z) + \overline{w'e'} + \frac{1}{\rho}\overline{w'p'} \qquad (1)$$

where the first two terms on the right-hand-side represents the flux of mean flow kinetic energy, and the second two represent the rate of diffusion of kinetic energy. Over land, we often assume that the energy flux through the ground is negligible, such that the flux entering the layer at height h can be related to the total rate of dissipation within the layer by

$$\int_0^h \epsilon\, dz = -F(h) + \frac{g}{T_v}\int_0^h \overline{w'T_v'}dz \qquad (2)$$

where the second term on the right-hand-side accounts for the generation of kinetic energy due to any buoyancy flux. For neutral conditions, this expression states that the flux of kinetic energy into a layer is balanced by the total rate of dissipation within that layer.

Over the ocean, we expect the surface energy flux, which drives waves and currents, to be non-negligible. Expression (2) must be modified to take into account the energy into the ocean, $F(0)$, such that

$$\int_0^h \epsilon\, dz = -[F(h) - F(0)] + \frac{g}{T_v}\int_0^h \overline{w'T_v'}dz \qquad (3)$$

Therefore, less volume averaged dissipation is required to balance the same energy flux into the layer as long as there is a net flux into the ocean. In fact, the difference between the integrated dissipation rate and the total energy flux at the top of this layer can be used to roughly estimate the energy flux into the ocean.

2. SIMILARITY THEORY

In a stationary, horizontally homogenous, constant stress layer, the vertical derivative of the energy flux takes the form of the familiar TKE budget equation

$$\epsilon = -\overline{u'w'}\frac{\partial U}{\partial z} - \overline{v'w'}\frac{\partial V}{\partial z} - \frac{\partial \overline{w'e'}}{\partial z} - \frac{1}{\rho}\frac{\partial \overline{w'p'}}{\partial z} + \frac{g}{T_v}\overline{w'T_v'} \qquad (4)$$

MO scaling provides us with a dimensionless form of the TKE budget given by

$$\phi_\epsilon(\frac{z}{L}) = \frac{\epsilon \kappa z}{u_*^3} = \phi_m(\frac{z}{L}) - \phi_e(\frac{z}{L}) - \phi_p(\frac{z}{L}) - \frac{z}{L} \qquad (5)$$

where L is the MO length, κ is the von Karman constant, and u_* is the friction velocity. This expression is often used to estimate the momentum over the ocean from estimates of the dissipation rates and a parameterization of ϕ_ϵ from

$$\rho u_*^2 = \rho[\epsilon \kappa z/\phi_\epsilon(z/L)]^{2/3} \qquad (6)$$

This type of parameterization should be valid as long as the measurements are made above the WBL and the constant flux assumption holds. However, an additional forcing mechanism is introduced due to the presence of surface waves as we approach the surface. In this region (i.e., the WBL), MO similarity is expected to break down. For example, in the WBL the velocity can be decomposed into mean, turbulent, and wave-induced components

$$u(t) = U + u'(t) + \tilde{u}(t) \qquad (7)$$

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An Investigation of the Wave-Induced Momentum Flux over the Open Ocean

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ABSTRACT

This study presents an investigation of the influence of the dominant wind-driven surface waves on the vertical flux of horizontal momentum in the marine surface layer for open ocean conditions. Previous investigators have used phase averaging to remove the turbulence from an oscillatory signal, but the absence of a monochromatic wave field in open ocean conditions complicates this approach. We overcome this difficulty by choosing time periods characterized by the most monochromatic-like waves present and filtering those sections of wind data with a narrow band-pass filter centered around the dominant wave frequency. The filtered wind fields are then phase averaged at the corresponding period of the dominant waves to isolate the wave-induced components of the atmospheric fluctuations. The product of the vertical and horizontal components are computed over all phases of the wave to generate vertical profiles of the wave-induced momentum flux. The dependence of wave-induced momentum flux on sea state is investigated by bin averaging the normalized flux according to wave age. This results in a set of profiles which express the ratio of the wave-induced momentum flux to the total flux as a function of the wave age parameter c/u_*, where c is the phase speed of the dominant wind-wave and u_* is the friction velocity. These profiles provide strong quantitative evidence that there is a significant flux of momentum to the atmosphere from decaying waves, and a transfer of atmospheric momentum to developing waves from the atmosphere. The vertical structure of these profiles share a number of similar features with previous laboratory and numerical studies. The results indicate that the upper edge of the wave boundary layer corresponds to a dimensionless height kz of O(1), where k is the wavenumber of the dominant wind-waves and z is the height above the mean sea surface.

1. Introduction

The exchange of momentum, heat, and mass across the air-sea interface plays an important role in determining the dynamics and thermal properties of the atmosphere and the ocean. In order to understand either media, it is essential to understand how they interact through the transport or flux of quantities across their common boundary. For modeling applications, these